

Dispersal of Galactic Magnetic Fields into Intracluster Space

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Abstract

Little is known about the origin and basic properties of magnetic fields in clusters of galaxies. High conductivity in magnetized interstellar plasma suggests that galactic magnetic fields are (at least partly) ejected into intracluster (IC) space by the same processes that enrich IC gas with metals. We explore the dispersal of galactic fields by hydrodynamical simulations with our new *Enzo-Galcon* code, which is capable of tracking a large number galaxies during cluster assembly, and modeling the processes that disperse their interstellar media. Doing so we are able to describe the evolution of the mean strength of the field and its profile across the cluster. With the known density profile of dispersed gas and an estimated range of coherence scales, we predict the spatial distribution of Faraday rotation measure and find it to be consistent with observational data.

1 Introduction

Direct evidence for magnetic fields in intracluster (IC) gas comes from measurements of extended radio emission in many (tens) of clusters, and from Faraday rotation measurements in several clusters (reviewed by Ferrari et al. 2008, Carilli & Taylor 2002). Estimates of the mean

strength of the field across the radio emitting region are not very reliable because of the need to assume a relation between the field and particle (both electrons and protons) energy densities. The validity of the commonly made assumption of energy equipartition in extragalactic environment of clusters is questionable. When equipartition is assumed, field values in the range $O(0.1-1 \mu\text{G})$ are typically deduced. A reliable lower limit on the mean strength of the field, typically $0.2 - 0.4 \mu\text{G}$, is obtained when an upper limit is set on nonthermal X-ray emission from the radio-emitting electrons (reviewed by Rephaeli et al. 2008).

Generally, IC magnetic fields could either arise from cosmological seed fields generated in the early universe (reviewed, e.g., by Grasso & Rubinstein 2001) that are directly amplified by turbulent processes (e.g., Kunz et al. 2010), or from dispersal of fields from the cluster galaxies (Rephaeli 1988). Irrespective of whether very weak primordial fields can indeed be efficiently amplified to the above range, the possibility of a major contribution to IC fields by magnetized galactic plasma should be further explored. The motivation to do so is quite clear: IC gas has a major galactic component, as clearly indicated by the fact that the gas is metal-enriched. When metals were transferred out of galaxies - by galactic winds and ram-pressure stripping - interstellar fields embedded in the plasma were carried along. In this scenario essentially all the cluster ellipticals (i.e., most of the galaxies in a rich cluster) have contributed to the build up of IC fields. A significant contribution could have come from a few active galaxies, such as dominant radio galaxies (e.g., the Coma cluster; Wilson 1970), or AGN (as has recently been simulated by Xu et al. 2009), but due to the very uncertain statistics of active galaxies in clusters this contribution is difficult to quantify. On the other hand, the contribution of cluster ellipticals can be readily gauged by their related metal feedback into IC gas.

Aside from general expectation and simple estimates, a detailed description of the stripping of magnetized interstellar (IS) media and their direct implications on IC magnetic fields has not yet been given. The process is obviously too involved to be described analytically, but can be simulated numerically with a hydrodynamical code that has the capability of tracking the cluster galaxies. We have recently enhanced the powerful adaptive mesh refinement (AMR) hydrodynamical *Enzo* code (Bryan & Norman 1997) by adding an algorithm to identify

and track a relatively large number of galaxies during the course of cluster evolution. In our expanded code a galaxy is identified early in the proto-cluster evolution, and described subsequently in terms of a galaxy construct, or *galcon*. Results from the first implementation of our *Enzo-Galcon* code to model the ejection and transport of gas and metallicity into IC space by ram-pressure stripping and galactic winds were described by Arieli, Rephaeli & Norman (2008, 2010, hereafter ARN1, and ARN2). To assess the viability of possibly dominant galactic origin of IC magnetic fields, we used this (non-MHD) *Enzo-Galcon* to describe the ejection of magnetized plasma out of *galcons*, and determined the spatial distribution and evolution of IC fields. In this paper we describe the simulations and the deduced properties of IC fields.

In Section 2 we briefly describe the *Enzo-Galcon* code and our modeling of the ejection of magnetized IS plasma. The main results from the first *Enzo-Galcon* simulation are presented in section 3. We end with a brief discussion in Section 4.

2 Simulation and Modeling

To describe the evolution of ejected galactic magnetized gas we performed a high resolution simulation with the *Enzo-Galcon* code in the context of the Λ CDM cosmological model, with matter and dark energy density parameters $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, respectively, and mass variance normalization $\sigma_8 = 0.9$ (taking $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The code root grid includes 128^3 cells which cover a comoving volume of 54^3 Mpc^3 with two nested inner grids. The highest refined sub-grid covers a comoving volume of 27^3 Mpc^3 divided into 128^3 cells; this can be further refined adaptively by up to 5 levels, with a maximum ~ 9 kpc resolution. We enforce maximum refinement in the vicinity of *galcons*, and 9 kpc is the resolution for gas exiting the galaxies.

The simulation was initialized at $z = 60$ and evolved until it was stopped at $z_r = 3$, the (‘replacement’) redshift when early galaxies were already well developed and (as indicated by observations) star formation rate (SFR) peaked. At this time a halo-finding algorithm was employed to locate 89 galactic halos with masses in the range $10^9 - 10^{12} M_\odot$ within a volume

which eventually collapsed to form a rich cluster with total $M = 5.4 \times 10^{14} M_{\odot}$, and virial radius $R_V = 1.7$ Mpc (ARN2). The baryonic contents of these halos were analyzed and replaced by *galcons*, with the baryon density profile in each *galcon* fit by a β model. Both stellar and gaseous components are included in *galcons*, and since stars form in the same IS high gas density regions that contain most of the gas and can be assumed to have initially roughly similar spatial distributions, it is reasonable to approximate both by the same β -profile parameters, but with different central densities (see ARN2 for details).

Galcons with these analytic density profiles are inserted into the centers of each halo, and assigned the halo velocity. Each *galcon's* central density and outer radius are determined from the fit and the value of the baryonic mass within the halo virial radius. An equal amount of baryons is removed from the simulated density field (without affecting the total mass density field, and thus preventing an unphysical instantaneous change in the simulated density distribution).

The mean initial baryonic mass density in galaxies can be determined by multiplying the mass density of halos from the Press & Schechter (PS, 1974) mass function by the universal baryonic density parameter Ω_b . The stellar mass density is calculated by integrating the cosmic SFR density (to be specified below) over the interval $[z_i, z_r]$.

Upon initialization of the *galcons* the simulation was resumed and evolve to $z = 0$. The motion of *galcons* was tracked using Enzo's N-body machinery. We followed mass and energy ejection processes - galactic winds and ram pressure stripping - through simple analytic models. Galactic winds reduce the total stellar mass while ram pressure stripping continuously reduces the *galcon* outer gas radius (as quantified below). Since galactic winds are SN driven, their elemental abundances are higher than in IS gas by a factor of ~ 3 . Metal enrichment by each of the two processes is followed separately.

During cluster collapse and ensuing episodes of galaxy and subcluster mergers, IS media are partly stripped by tidal interaction between galaxies. As IC gas density builds up, ram-pressure stripping becomes increasingly more effective, especially in the central, higher density region. We quantify this hydrodynamical process by determining for each *galcon* (at all time steps) the

stripping radius, where local IC gas pressure is equal to the local galactic IS pressure. It is simply assumed that all IS gas outside this radius is stripped in a relatively short dynamical time. [We generalize the analytic Gunn & Gott (1972) stripping condition by including the contribution of DM to the galactic gravitational potential.] Observational evidence supports the expectation that stripping truncates the gaseous disk but does not modify the gas profile, nor appreciably affects the dynamics of the stellar and DM components of the galaxy (Kenney & Koopmann 1999, Kenney, Van Gorkom & Vollmer 2004). Thus, the outer radius of the *galcon* gas component is reduced to the stripping radius without modifying the central density or the scale radius of its profile.

Galactic magnetic fields have a wide spectrum of scales over which the field changes direction. These ‘coherence’ scales are in the range $l \sim 0.1 - 10$ kpc, with the smallest ‘cells’ reflecting local plasma conditions and processes, and the largest scale arising from the action of galactic dynamo (Carilli & Taylor 2002). In ‘normal’ spiral galaxies values of the mean field on both these small and large scales are in the range $1 - 10 \mu\text{G}$ (Beck 2005); in our estimates we scale galactic fields to a characteristic mean (volume-averaged) value of $3 \mu\text{G}$. Even though most cluster galaxies evolve from spirals to ellipticals (as an integral part of cluster formation and evolution), and partial stripping of their IS gas itself reflects this change, we note that mean field values in this range are typically deduced also in ellipticals (Mathews & Brighenti 1997). When magnetized IS gas with such a spectrum of coherence scales is stripped the very high electrical conductivity in the plasma essentially ensures that fields are anchored to the outflowing gas (Rephaeli 1988). During the motion of a magnetized cell out of the higher density IS environment it expands and its density n decreases; consequently, ‘flux freezing’ implies that the mean field weakens according to $B \propto n^{2/3}$.

Given that galactic fields are distributed in what are essentially separate regions with a spectrum of sizes, and that fields are frozen in the stripped gas, we simplify the treatment of the field transfer to IC space by assuming that cells are stripped out of their parent *galcon* essentially in tact. This is realistic for cells that are appreciably below a typical galactic size, $l \leq 10$ kpc, namely for most (if not all) the range of coherence scales. While we do attain the

highest level of spatial resolution, $\sim 9\text{kpc}$ (implementing a geometric refinement capability of the *Enzo-Galcon* code) in the description of all the baryonic processes in *galcons*, this resolution limit is insufficient for following the evolution of cells with lower coherence scales. Consequently, we cannot address any aspect of the magnetic field dispersal process that is affected by the coherence scale. In fact, this limitation is the main reason for restricting our modeling of the field to mean scalar properties.

The build-up of magnetic field energy density in IC space is described as follows: At each time interval the increase in the IC magnetic field energy density is calculated by subtracting its volume-weighted value at the beginning of the time interval from its value at the end of the interval. The product of the *galcon* initial velocity and the time interval provides a measure of the radial extent of a spherical shell across whose volume the field is re-distributed. This procedure is repeated until gas stripping out of *galcons* is negligible.

3 Results

3.1 Evolution and distribution of IC fields

The rise in the central and volume-averaged values of the field as magnetized plasma continues to accumulate in IC space is described in Figure 1. Late time evolution of the field is more rapid when ram-pressure stripping becomes increasingly more effective. Evolution of the field is essentially passive - no amplification or reconnection is assumed, simply because it is difficult to assess the effectiveness of these processes in clusters.

The profile of the mean field, $\langle B^2 \rangle^{1/2}$, averaged over spherical shells, is shown in Figure 2, with a central value $B_0 \simeq 0.9 \mu\text{G}$ (scaled to a mean galactic source field of $3 \mu\text{G}$). As we have previously shown (ARN2), the gas density and metallicity distributions can be well described by a profile with core radius in the $200 - 300 \text{ kpc}$ range, as observed in similar high-mass clusters (e.g., Sun et al. 2009). Similarly, we fit the profile of $\langle B^2 \rangle^{1/2}$ by a β model, $B_0(1 + r^2/r_B^2)^{-3\beta/2}$; the fit (shown in Figure 2) yields $r_B \simeq 350 \text{ kpc}$, and $\beta \simeq 0.94$.

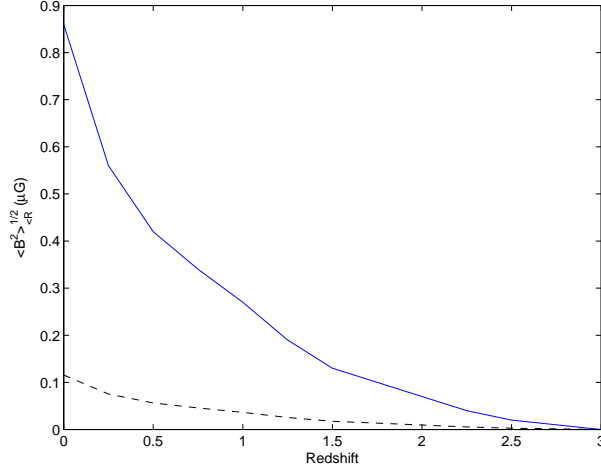


Figure 1: Redshift evolution of the field central value (blue line), and its mean volume-weighted value over a region with radius of 1 Mpc (black dashed line).

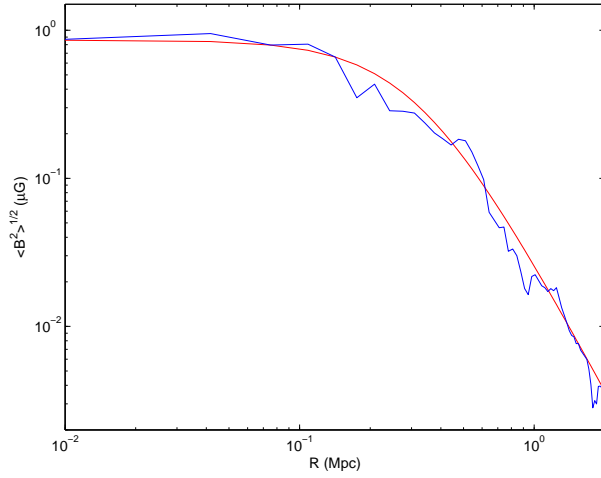


Figure 2: Mean magnetic field as a function of radial distance from the cluster center (blue line) and the best fit to a β -profile (red line). The volume-weighted mean field is an emission-weighted average that was calculated assuming (electron) synchrotron emission scales as B^2 ; see the text for more details.

3.2 Comparison with observational results

Lack of spatial information on IC fields limits comparison with observational results to just the mean field strength. The latter has been estimated from observations of radio synchrotron emission and FR measurements, for which we need to compute the respective field measures, volume average for the former, and a density weighted line-of-sight average for the latter. We emphasize that even with these measures comparison with observational results is not very meaningful due the fact that in observational analyses the field (and, in the case of synchrotron emission, also the electron density) are assumed not to vary across the cluster.

Measurements of IC synchrotron emission by relativistic electrons can be analyzed to determine the volume-average value of the mean (orientation-averaged) magnetic field, if a relation - such as equipartition - is assumed between the energy densities of particles (electrons and protons) and fields. If p is the power-law index of the electron differential number density as function of the Lorentz factor, $n(\gamma) \propto \gamma^{-p}$, then the emitted flux scales as $B^{(p+1)/2}$, and since typical values of power-law indices of extended IC regions of radio emission are in the range $1 - 2$ (Rephaeli et al. 2008), $p \geq 3$. Therefore, the emission scales at least as steeply as B^2 . This scaling is used in the calculation of the volume-weighted average of the field, shown in Figure 3. With our adopted β profile for the gas density (and the assumption of flux-freezing), the volume-weighted mean field is nearly constant in the inner ~ 100 kpc region, beyond which it decreases steeply from a central value of $B_0 \simeq 0.9 \mu\text{G}$ to $\simeq 0.3 \mu\text{G}$ and $\simeq 0.1 \mu\text{G}$ at 0.5 Mpc and 1 Mpc, respectively. These estimates are in the typically deduced range of $0.1 - 1 \mu\text{G}$ (e.g., Ferrari et al. 2008), and are in agreement with estimates of the fields from joint analyses of radio and high-energy X-ray emission in several clusters (Rephaeli et al. 2008), if this emission originates in Compton scattering of the radio-emitting electrons by the CMB (Rephaeli 1979).

The strength of IC fields has also been deduced from Faraday rotation of the polarization plane of radiation from radio galaxies located within, or lying behind clusters. Assuming a magnetic field morphology with cells of constant size, density, magnetic field strength, but with a random orientation inside each cell, the contribution to the rotation measure (RM) from each

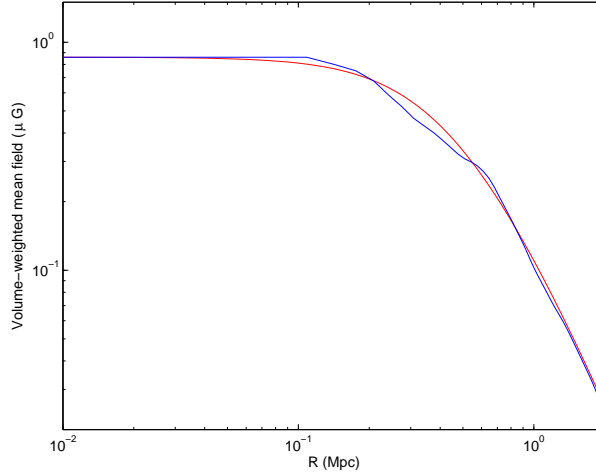


Figure 3: Volume-weighted mean magnetic field as a function of radial distance from the cluster center (blue line), and its fit to a β -profile (red line).

cell is given by

$$RM = 812 \int_L^0 n_e B_{\parallel} dl \text{ (rad m}^{-2}\text{)}, \quad (1)$$

where n_e is the thermal electron density in cm^{-3} , B_{\parallel} is the line-of-sight magnetic field in microgauss, and L is the path length in kpc. The precision with which the mean strength of IC fields can be determined is limited by their unknown morphology, by selective sampling of fields in the cluster core, and by considerable modeling and systematic uncertainties. There typically are only a few background radio galaxies located at different radial distances with respect to the cluster center, usually necessitating a statistical ‘stacking’ analysis of a relatively small cluster sample. The spatial distribution of the field can only be inferred statistically from RM measurements of a large sample of clusters.

The distribution of RMs is generally patchy, indicating that large-scale magnetic fields are not regularly ordered on cluster scales, but have structures on scales as low as a few kpc. However, because the exact range of coherence scales is unknown, the interpretation of RM data assuming a constant scale over the entire cluster volume is clearly an oversimplification that introduces a substantial modeling uncertainty. Indeed, Newman et al. (2002) demonstrated that the assumption of a single-scale magnetic field leads to an overestimation of the magnetic

field from RM data.

To demonstrate this uncertainty, we calculated the RM for our simulated cluster using three different coherence scales spanning the range discussed in the literature: $\lambda = 9, 18$, and 45 kpc. For each of these scales we computed an average magnetic field over all the cells that are contained in a region with a corresponding size, and selected a random orientation of the field, to account for the fields stochastic nature. The results are plotted in Figure 4, together with results from the statistical sample of RMs in 16 relaxed clusters from Clarke et al. (2001), and our best-fit to the measured values. While the comparison of our results with the composite profile (from 16 different clusters) has only limited meaning, the RM declining profile is roughly similar to the pattern seen in the data (even though some of the low-significance data at small radii are significantly higher than predicted by the model). Specifically, the best-fit line to the data matches well the predicted profile for a coherence scale of $\lambda \sim 18$ kpc.

It is instructive to contrast our predicted mean field strength with that of Clarke et al. (2001), who derived a mean value of $\sim 5 \mu\text{G}$, assuming a coherence scale of 10 kpc. For our fiducial value $B_0 \simeq 0.9 \mu\text{G}$, the mean coherence scale that we deduce is roughly twice the value assumed by Clarke et al. This would seem to suggest that these results are roughly in agreement, since for a randomly oriented fields the mean field value deduced from FR measurements scales as λ^{-2} . Given the inherent indeterminacy in deriving both the mean field and the coherence scale from a single observable, the choice made by Clarke et al. is obviously not unique, even if admissible. While our predicted value for the mean field is, strictly speaking, a fiducial value based on scaling of the galactic source field to a value of $\sim 3 \mu\text{G}$, this value is realistic and unlikely to be an underestimate by a more than $\sim 50\%$. Thus, our model provides a physical basis for realistically estimating the mean value of IC fields, in contrast to the much higher value adopted by Clarke et al. (2001), a value which is essentially based on an arbitrary choice for λ .

In a more realistic description a range of values for the coherence scale should be taken for determining the RM distribution across the cluster. To do so we assume that the distribution of coherence scales can be well approximated by a Kolmogorov spectrum of cells with sizes in

the range $[\lambda_1 - \lambda_2]$. Support for this assumption can be found in the recent simulations of Xu et al. (2010). In the context of our model of galactic origin for the fields this range is expected to correspond to the adiabatically expanded typical range in galaxies. Since the latter range is roughly a fraction of a kpc to few kpc, it is expected that the corresponding IC range is higher by a factor of $3 - 6$, based on $n^{-1/3}$ scaling of IC to IS plasma density ratio. Because the resolution limit in our simulated cluster is 9 kpc, we sample the expected range by taking $\lambda_1 = 9$ kpc and $\lambda_2 = 45$ kpc. This is only a rough estimate intended solely for gauging the impact of taking a range of coherence scales (rather than just a single value).

The predicted RM profile, shown in figure 4 (solid green line) is - not surprisingly - systematically higher than for the case of a single coherence scale with $\lambda < 45$ kpc. More importantly, the fact that this profile is above the best fit line to the RM data at (essentially) all radii, clearly demonstrates that the mean strength of the field need not be high for consistency with the RM measurements. This conclusion is only strengthened when we explicitly account for the considerable uncertainty in the data, and is also quite insensitive to the exact shape of the assumed spectrum, as long as it is a typical turbulent spectrum with a characteristic rise with scale (λ).

4 Discussion

We present here results from cluster simulations with the *Enzo-Galcon* code incorporating a simple description of the ejection (by galactic winds) and ram-pressure stripping of magnetized IS media from cluster galaxies, and the direct implications on IC magnetic field. We show that magnetic fields anchored to the gas ejected and stripped out of galaxies can efficiently spread throughout the cluster volume, building a realistic declining spatial distribution for IC magnetic fields. In this approach we use a simple model for the origin of IC fields that does not invoke field amplification by mechanisms whose viability in the cluster environment is uncertain. Although field amplification may occur in some clusters it is questionable whether this can be generally the case in most clusters. We believe that the (relatively) minimalistic approach of a galactic

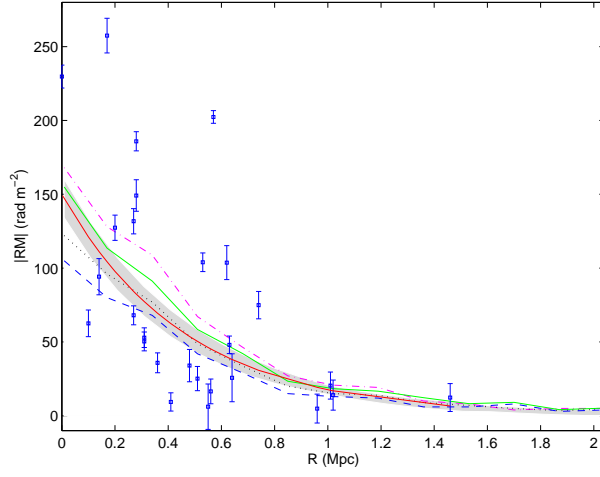


Figure 4: Comparison of RM from the simulated cluster with observational data from 16 relaxed clusters from Clarke et al. (2001). We show the predicted RM profiles for coherence lengths of 9, 18 and 45 kpc by the blue dashed line, black dotted line and magenta dashed-dotted line, respectively. The green line is the RM curve calculated from a Kolmogorov coherence scale spectrum. The best fit to observational data and the $1\text{-}\sigma$ uncertainty are shown by the red line and grey region, respectively.

origin for IC fields (Rephaeli 1988) provides a reasonable basis for gauging the main properties cluster fields.

Other contributions to IC fields could possibly be field amplification in small scale flux tubes (Ruzmaikin, Sokoloff & Shukurov 1989) or during merger shocks (Roettiger, Stone & Burns 1999). Magnetized plasma from radio galaxies (Kronberg et al. 2001) and AGN (e.g., Xu et al. 2009, 2010) could possibly contribute appreciably to IC the fields, but perhaps not ubiquitously, given the rarity of these sources as compared with normal galaxies. Xu. et al. (2009, 2010) carried out an MHD simulation with the *Enzo* code in order to follow the evolution of the magnetic field carried out by jets of a powerful AGN in the cluster center. Their simulation demonstrated that the ejected fields can be well spread throughout the cluster, and are amplified by gas turbulence during cluster evolution. The final field profile was found to be relatively flat, if AGN injection occurs before major mergers. AGN injection after major mergers results in more centrally peaked magnetic field distributions. But based on other MHD simulations (Dolag et al. 2001) it was concluded that in hierarchical formation of clusters, a correlation between RM and the X-ray surface brightness is expected to reflect the correlation between the magnetic field and gas density. Analysis of RM and X-ray brightness data for A119 led these authors to deduce that $B \propto \rho^{0.9}$, somewhat steeper than the slope we deduced in our model.

A more elaborate treatment of the evolution of IC fields was attempted by Donnert et al. (2008), who carried out a cosmological MHD simulation of clusters and explored a wide range of relevant parameters in galactic outflow models. While their approach is very different from our more minimalistic treatment, they too found out that IC fields generally have declining spatial profiles with predicted RM distributions that are in agreement with the observational results of Clarke et al. (2001).

The attractiveness of the galactic origin model for IC fields is further enhanced by the fact that it naturally yields relatively high $\sim 1 \mu\text{G}$ field in the central region and the (very reasonable) expectation of an appreciably declining radial profile outside the core. These properties are in full agreement with measurements of radio emission and RM data. Moreover, the magnetic field energy within even 0.5 Mpc (spherical) region is more than a hundred times smaller

than for the case of a constant $\sim 5\,\mu\text{G}$ field.

Given the rudimentary level of our understanding of magnetic fields and nonthermal phenomena in clusters, more comprehensive observational and theoretical studies are needed in order to determine the full range of possible sources of IC magnetic fields and nonthermal particles. Extensive radio measurements of many more clusters are needed to obtain more detailed information on the spatial distributions of the emission and RMs. Our simulation work will continue with the considerably improved *Enzo-Galcon* code.

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